



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

A Laser Technology Test Facility for Laser Inertial Fusion Energy (LIFE)

A. J. Bayramian, R. W. Campbell, C. A. Ebbers, B. L. Freitas, J. Latkowski, W. A. Molander, S. B. Sutton, S. Telford, J. A. Caird

October 9, 2009

Journal of Physics Conference Series

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

A Laser Technology Test Facility for Laser Inertial Fusion Energy (LIFE)

**A.J. Bayramian, R.W. Campbell, C.A. Ebberts, B.L. Freitas, J. Latkowski,
W.A. Molander, S.B. Sutton, S. Telford, and J. A. Caird**
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550, USA

bayramian1@llnl.gov

Abstract. A LIFE laser driver needs to be designed and operated which meets the rigorous requirements of the NIF laser system while operating at high average power, and operate for a lifetime of >30 years. Ignition on NIF will serve to demonstrate laser driver functionality, operation of the Mercury laser system at LLNL demonstrates the ability of a diode-pumped solid-state laser to run at high average power, but the operational lifetime >30 yrs remains to be proven. A Laser Technology test Facility (LTF) has been designed to specifically address this issue. The LTF is a 100-Hz diode-pumped solid-state laser system intended for accelerated testing of the diodes, gain media, optics, frequency converters and final optics, providing system statistics for billion shot class tests. These statistics will be utilized for material and technology development as well as economic and reliability models for LIFE laser drivers.

1. Introduction

The search for a source of green, carbon-emission-free power source is perhaps one of our most important activities in the twenty first century. Of the many technologies under consideration, the way to harness the most energy from the least amount of fuel is to use nuclear power. In response to this logic, nuclear fission power plants dot the globe, yet they have not entirely taken over the power industry due to issues with nuclear waste storage and weapons proliferation. The “other” nuclear power is nuclear fusion, the same power that fuels our sun and all the stars we see in the sky. Understanding of the efficiency and cleanliness of this power source has generated over fifty years of research and development as we try to harness this process on earth.

For the first time, there are several projects underway worldwide which promise to demonstrate fusion ignition and gain > 1. The first of these facilities to be completed is the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). In 2010, the team of scientists and engineers operating the NIF will start a campaign to demonstrate fusion ignition, which could serve as the basis for a national program to develop Laser Inertial Fusion Energy (LIFE). A LIFE laser driver needs to be designed and operated which meets the rigorous requirements of the NIF laser system. In addition, the LIFE laser will have new requirements of operating at high average power and having a system lifetime of >30 years (10 billion shots). No laser has ever simultaneously met these requirements, yet a credible design must be based on relevant experimental demonstrations. Ignition on NIF will serve to demonstrate laser driver functionality. Previous operations of the Mercury laser system at LLNL have demonstrated the ability of a diode-pumped solid-state laser to run at high average power. However, the final system lifetime requirement of >10 billion shots remains unproven.

One of the first steps toward demonstrating laser viability over a 30 year period is an accelerated test of the basic components and technologies. Proven components and technologies could then be

assembled in a full scale laser demonstrator where the engineering and durability would have a high probability of success (expense higher and risk necessarily lower). To accomplish this task, we propose the construction of a Laser Technology Test Facility (LTF), a diode pumped solid state laser system which would operate at 100 Hz, which would enable billion shot tests in <6 months.

2. A 100-Hz Laser System

The LTF laser builds on laser technology and expertise developed at LLNL in both the NIF laser and the Mercury laser system [1]. The basic architecture is that of a master oscillator power amplifier (MOPA) with a fiber based oscillator that enables precision pulse shaping seeding larger aperture bulk amplifiers to produce the required energy.

The seed laser begins with a 15 mW continuous single mode oscillator. Since the gain peak of the Nd:YAG based amplifier is temperature dependent[2], a tunable source is required to maintain the oscillator at the effective gain peak of the diode-pumped power-amplifiers. Temporal shaping is performed using an integrated LiNbO₃ electro-optic Mach-Zehnder modulator controlled by a Highland Technologies arbitrary waveform generator. At the output of this system, the pulse energy is in the pico-Joule regime. To meet the micro-Joule energy input requirements of the pre-amplifier system, the pre-amplifier needs micro-Joule class energy, which is achieved with a three-stage fiber-amplifier system. Each stage utilizes polarization maintaining single mode ytterbium doped fiber amplifiers which provide 20 dB gain.

The pre amplifier chain begins with a collimated fiber launch from the final fiber amplifier providing a 6 mm beam with Gaussian spatial profile. The Gaussian is converted to a flat-top spatial beam profile using a refractive shaper (MolTech). To minimize diffractive ripple in the propagating beam, an apodizer is used to generate a 20th order superGaussian. An adaptive optic provides wavefront correction based on a wavefront sensor signal which is located in an amplifier diagnostic at the output of the system. After magnification, the beam passes through two stages of Faraday isolation and is imaged in the first amplifier head. The 10 mm aperture diode-pumped Nd:YAG amplifiers (Northrup Grumman) are capable of Joule class operation at > 100 Hz. The beam is image relayed to a second identical amplifier situated in a 4-pass angular-multiplexed, image-relayed cavity. When activated at 100 Hz, the amplifier heads have a thermal focal length which must be compensated to maintain collimated image relay. By decreasing the length of the relay telescopes, the transmitted beam is divergent and can exactly compensate the thermal lens providing a collimated beam. After passing through the amplifier, the beam is reflected by a mirror along a second multiplexing angle, enabling the beam to pass by the injection mirror, and hit a retro reflection-mirror. This reflected beam retraces the entire beam path back to the first amplifier, where a Faraday rotator ejects the pulse to the targeting telescopes.

The power amplifier is the heart of the LTF laser system, generating valuable diode array and diode driver lifetime data in addition to the 10-J, 100-Hz operation for testing potential LIFE optics. To achieve 1 kW average power, the power amplifier required custom design of the diode array, diode light delivery, and amplifier head to accommodate the increased thermal load.

The diode array technology builds on the SIMM [3] technology developed at LLNL for the Solid State Heat Capacity Laser (SSHCL). This diode packaging offers high average power and brightness in a simple, rugged, scalable architecture that is suitable for large two-dimensional arrays. While the diode bar and packaging technologies meet the needs of the LTF laser system (and perhaps LIFE), the diode power supplies are lacking. Current power supplies are limited to ~20 Hz, the cost per unit is excessive (~ \$1/W), and the pulsers are inefficient due to operational parameter adjustability, diagnostics, and the need for long cables between pulser and diode array. Of the many tasks facing the LIFE laser system, one of them is to reduce the cost and increase efficiency of diode pulsers. A new kind of pulser, named a “smart tile,” has been designed which is a miniaturized and simplified version of the current pulsers. The central design is based on the following key elements: remove all processing and adjustability, place the pulser in close contact to the diodes it is driving, and utilize the diode array backplane as the heatsink for the pulser. Using a circuit design program (SPICE, RD

Research), our “smart tile” model indicates these devices should meet performance requirements with a baseline component cost which is 40X lower in cost and 20X lower in size while being 15% higher in efficiency. This kind of pulser will be utilized on the LTF both to meet the demanding average power requirements and as a stepping stone towards LIFE technology. Just like the optics being tested in the output portion of the laser, the diode array and diode pulsers will also be tested in an integrated fashion for billions of shots.

The diode light delivery system for the amplifier represents a somewhat different than the duct approach previously used on Mercury [1], the mix of ducts and refractive optics in LUCIA[4], or the direct side pumping techniques used in HALNA [5] and other systems. In the fast axis direction (after microlensing $< 1^\circ$ degree divergence), the diode array is subdivided into individual columns of diode tiles (10 bar diode stacks). A prism is placed in front of each column and is used to direct the diode light toward the amplifier. Rather than focus the light, the diode emission is allowed to diverge to fill the amplifier aperture. The overlay of multiple diode array columns creates a high intensity pump profile without the need for ducting or focusing. Along the slow axis, where the divergence is close to 10° , a pair of cylindrical lenses is used to image the diode array onto the amplifier. Immediately preceding the amplifier, a very short refractive duct is used to clean up the edges of the pump profile to create a sharp edge to the beam thereby improving extraction efficiency and modefill (area of the extraction beam relative to the pump area). A FRED (Photon Engineering) ray-trace model was used to engineer an optimum solution for the array characteristics and amplifier size. The ray trace results include net absorption for the amplifier and indicate $>95\%$ energy delivered to the $2.5 \times 2.5 \text{ cm}^2$ aperture with peak-to-valley gain profile of 2:1. Since the diode brightness is conserved, the almost perfectly flat pump beam observed at the end of the duct propagates and diverges, which has an effect on the uniformity and edges of the beam. Still, considering the amplifier thickness is greater than the aperture size, the gain profile is surprisingly flat and sufficient for the LTF laser requirements.

The power amplifier for this high average power laser system requires careful thermal management and design to avoid beam modulation, depolarization, and thermally induced fracture of the amplifier slabs. At 100 Hz, the amplifier slabs must dissipate more than 660 W of thermal power or 105 W/cm^2 . As on Mercury, LUCIA, and many other slab amplifiers worldwide, an effective method of minimizing wavefront distortion is to remove the heat in a geometry which creates a quasi-one-dimensional thermal gradient along the same direction as the laser propagation. This geometry ensures that all parts of the propagating laser beam see the same set of thermal gradients and therefore the same index profile as the beam propagates through the system. To first order, a system designed in this way is athermal. For the LTF amplifier, the method we have chosen is to use sapphire, a tough transparent heatsink, since sapphire has a close refractive index and thermal expansion match to Nd:YAG. To mitigate losses due to amplified spontaneous emission (ASE), an edge cladding of SF14 (Schott Glass) doped with copper is bonded to the Nd:YAG perimeter. Using this geometry as the baseline design, a complete 3-D thermal model of the amplifier head was developed using code that was benchmarked on the Mercury laser [1]. The modeled thermal wavefront is approximately 33 waves of power and a residual wavefront that is nominally a 4th order stress induced edge effect (~ 5.4 waves). The power can be compensated with a small change in the relay telescope length and the higher order wavefront corrected by our adaptive optic in the pre-amplifier or even a static wavefront corrector as was demonstrated on the Mercury laser [1]. Although we have attempted to create a 1-D thermal gradient, the effect is not perfect since sapphire's thermal conductivity is far from infinite at room temperature ($\sim 30 \text{ W/m K}$). However, considering the average power of this Nd:YAG system, the temperature and thermal wavefront are reasonable and tractable.

The architecture of the LTF borrows from the experience gain on the Mercury laser and the NIF. The 10 J is extracted in four passes, passively switched by taking advantage of angular multiplexing. Utilizing a relatively large multiplexing angle ($\sim 1^\circ$), the 100 mJ injected beam is spatially separated from the other three passes through the system. After passing through the amplifier twice, the beam exits the telescope where a knife edge mirror sends the beam through a Pockel's cell for parasitic isolation. A second knife edge mirror re-injects the pulse for a 3rd and 4th pass through the system.

After the 4th pass, the pulse exits the system. The entire architecture comfortably fits on a 5'x16' table. For other applications, such as laser peening or pump source for optical parametric amplification (OPA), or Ti:sapphire based chirped pulse amplification systems, this architecture can be easily folded to a much smaller footprint.

3. Component Technology Testing

The central purpose behind the LTF is the accelerated testing of laser systems to shot counts relevant to the lifetime of a LIFE laser driver. At 13 Hz, a LIFE plant would accumulate 12.3 billion shots in 30 years. Development of the materials for LIFE will require all of the quality control, materials purification, fabrication, polishing, and coating developments that have occurred as part of the NIF development and more. To get the most data and statistics from a test, our strategy is to expose many multiple samples of many different kinds of optics simultaneously. By placing optics that have a higher probability of survival upstream from optics that are more questionable, downstream modulation can be minimized. To maintain the flat-top beam and further minimize downstream modulation, image relay telescopes are used to reimage the beam between different types of optics. The image relay minimizes nearfield modulation, allows beam cleanup utilizing pinholes in the relay telescopes, and adds the freedom to change the beam diameter / testing fluence on different kinds of optics. Testing results will be incorporated into optical lifetime models, system availability models, and economic models. Just like material developments for the NIF, the results will also be used in iterative development loops aimed at improving fabrication and finishing processes for the optics as well as testing mitigation techniques for passivating optical defects or repairing optics. There are two baseline testing strategies: cm² small area testing for 6 months will generate 1.6 billion shots which is a significant fraction of LIFE plant lifetime, and full aperture raster scanning using the cm² beam which in 6 months would generate millions of shots.

In addition to the optical testing, the diode array technology will also be tested including: diode bars, diode packaging, diode pulsers, and the integrated array unit. Finally, the long term tests indirectly test the computer controls, data acquisition, diagnostics, and support equipment. Our intent is that the LTF serve as a scale model of a LIFE driver beamline, containing many of the control points, optics, and diodes tested at LIFE driver relevant levels. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

- [1] Bayramian A, Armstrong P, Ault E, Beach R, Bibeau C, Caird J, Campbell R, Chai B, Dawson J, Ebberts C, Erlandson A, Fei Y, Freitas B, Kent R, Liao Z, Ladran T, Menapace J, Molander B, Payne S, Peterson N, Randles M, Schaffers K, Sutton S, Tassano J, Telford S and Utterback E, 2007 The Mercury Project: a high average power, gas-cooled laser for inertial fusion energy development *Fus. Sci. & Tech.* **52** 383-7
- [2] Kimmelma O, Tittonen I and Buchter SC 2008 Thermal tuning of laser pulse parameters in passively Q-switched Nd:YAG lasers *Appl. Opt.* **47** 4262-6
- [3] Skidmore JA, Freitas BL, Crawford J, Satariano J, Utterback E, DiMercurio L, Cutter K and S. Sutton 2000 Silicon monolithic microchannel-cooled laser diode array *Appl. Phys. Lett.* **77** 10-12
- [4] Chanteloup JC, Yu H, Bourdet G, Dambrine C, Ferré S, Fülöp A, Le Moal S, Pichot A, Le Touzé G and Zhao Z 2005 Overview of the Lucia laser program: towards 100 Joules, nanosecond pulses, kW averaged power, based on Ytterbium Diode Pumped Solid State Laser *Solid State Lasers XIV: Technology and Devices, Proc. SPIE 5707*, edited by Hanna J. Hoffman, Ramesh K. Shori, (SPIE, Bellingham, WA, 2005) 105-16
- [5] Kawashima T, Kanabe T, Matsumoto O, Yasuhara R, Furukawa H, Miyamoto M, Sekine T, Kurita T, Kan H, Yamanaka M, Nakatsuka M and Izawa Y 2006 Development of Diode-Pumped Solid-State Laser HALNA for Fusion Reactor Driver *Elec. Eng. in Jap.* **55** 27-35